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Investigation on the dehumidification performance of $LiCl/H_2O$-MWNTs nanofluid in a falling film dehumidifier

Tao Wen, Lin Lu*, Hong Zhong

Renewable Energy Research Group, Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China

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ABSTRACT

Nanofluids could enhance both the heat and mass transfer performance due to its outstanding thermal properties. However, most previous studies only focused on the heat transfer while the mass transfer performance of nanofluids is seldom examined. In the paper, it proposed a novel $LiCl/H_2O$-MWNTs nanofluid for dehumidification by adding multi-walled carbon nanotubes (MWNTs) into Lithium chloride (LiCl) solution. The stable LiCl/water-MWNTs nanofluid was prepared by adding surfactant polyvinyl pyrrolidone (PVP) through mechanical methods. The concentration of MWNTs and PVP were 0.1 wt% and 0.4 wt% respectively. The influences of various parameters on dehumidification performance of $LiCl/H_2O$ solution, $LiCl/H_2O$-PVP solution and $LiCl/H_2O$-MWNTs nanofluid were investigated and compared. The experimental results show that $LiCl/H_2O$-PVP solution and nanofluid can enhance the dehumidification rate by up to 26.1% and 25.9% as a result of contact angle reduction. The contact angles decrease from 58.5° for LiCl solution to 28° and 26.5° for the two modified solutions respectively, the wetting areas increase from 0.172 m^2 to 0.209 m^2 and 0.210 m^2, and the film thickness reduces from 0.681 mm to 0.583 mm and 0.577 mm correspondingly. However, the dehumidification enhancement of nanofluid can be only attributed to the adding of surfactant, and the adding of 0.1 wt% MWNTs has undetected effect on the dehumidification performance in the present study. The results can provide some guidance for the mass transfer enhancement in liquid desiccant dehumidification in terms of adding surfactant and nanoparticle.

1. Introduction

Liquid desiccant cooling system (LDCS) has been considered as a promising alternative for the conventional vapor compression cooling system (VCS) [1]. Different with the VCS who removes the humidity load by cooling the temperature of processing air under dew point temperature, the LDCS absorbs the extra water vapor of the processed air through the partial water vapor pressure difference between the air and liquid desiccant. In consequence, it deals with the latent load individually by the sources of solar energy or waste heat, which leads to higher system efficiency and more comfortable indoor environment. Dehumidifier, as a key component in the LDCS, plays the role of water vapor absorption and influences the system performance notably. Therefore, how to improve the dehumidification performance becomes a meaningful focus for researchers.

Generally speaking, the mass enhancement technologies can be classified into two main types: physical method and chemical method. The former one improves the mass transfer by enhancing the wettability of contact surface with structure modification [2–4] or strength the turbulence of liquid film with mechanical disturbance [5,6]. For the latter one, the wettability of contact surface is improved with chemical techniques, such as surface treatment by super hydrophilic coating [1,7], and the addition of surfactant [8,9] or nanofluid [10,11]. The present study put its concentration on the adding of nanofluid and related investigations in this field will be presented in the following.

Nanofluid is defined to be the stable lyosol with ultrafine particles of diameter less than 100 nm [12]. It is fabricated by dispersing nanoparticles into base fluid through mechanical and chemical methods. In recent years, it has drawn more and more attention since it was observed with enhancement in heat and mass transfer [10,11]. For heat transfer, various degrees of enhancement were found for water and other base fluids with the adding of different kinds of nanoparticles, such as Cu, Al_2O_3, Fe, SiO_2 [13,14]. Compared with the attention drawn in heat transfer, the study on mass transfer of nanofluids is still limited.

Some investigators studied the bubble absorption characteristics of nanofluids [15–21]. Kim et al. [15] investigated the effects of three different kinds of nanoparticles on the absorption performance in NH_3/H_2O solution. Their experimental results indicated that the absorption

* Corresponding author.
E-mail addresses: vivien.lu@polyu.edu.hk, feitian010920215@163.com (L. Lu).

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Nomenclature

d	Absolute humidity(g/kg)
G	Mass flow rate(kg/s)
h	Enthalpy(kJ/kg)
LDCS	Liquid desiccant cooling system
LiCl	Lithium Chloride
*MWNT*s	Multi-walled carbon nanotubes
Δm	Dehumidification rate (g/s)
PVP	Polyvinyl pyrrolidone
T	Temperature(°C)
VCS	Vapor compression system
X	Concentration(%)

Greek symbols

φ	Relative humidity(%)
ρ	Density(kg/m^3)
Δ	Change value

Subscripts

a	Air
dry	Dry bulb
i	Inlet
o	Outlet
s	Solution
w	Cooling water

performance could be increased up to 3.21 times. Among the three kinds of particles, i.e., Cu, CuO and Al_2O_3, Cu was the most effective candidate. They contributed the absorption enhancement to the grazing effect proposed by Alper et al. [16]. Furthermore, Kim et al. [17] studied the effect of adding both surfactants and nano-particles to NH_3/H_2O on the behavior of bubble absorption. 2-ehtyl-1-hexanol, n-octanol and 2-octanol were employed as the surfactants. 5.32 times absorption rate improvement was observed with both 2-ehtyl-1-hexanol and Cu nano-particles. They recommended that the mass transfer performance could be improved significantly by adding surfactant and nano-particles simultaneously. Similar experiments were carried out by Ma et al. [18], who adopted carbon nanotubes (CNTs) as the nanoparticles. They stated that by using the surface treatment chemical method, the CNTs were dispersed into NH_3/H_2O solution evenly. Different from the conclusion drawn by Kim et al. [17] that the absorption improvement increased with the increase of nanoparticles concentration, Ma et al. [18] considered that there was an optimum particle concentration to achieve the highest absorption rate. In addition to the abovementioned nanoparticles, SiO_2 [19], Fe_3O_4 [20] and Ag [21] were also added into base fluids such like methanol for the purpose of mass transfer enhancement. Different levels of absorption enhancement were found in these studies.

Besides the bubble type absorption, falling film absorption is another type of mass transfer which is usually used in CO_2 absorption and absorption refrigeration systems [10]. Kang et al. [22] experimentally measured the water vapor absorption rate with the adding of Fe and CNTs nanoparticles of 0, 0.01% and 0.1 wt% in a tube falling film absorber. Their results revealed that the absorption rate was larger at higher concentration of nanoparticle. What is more, the addition of CNTs presented better mass transfer performance than Fe nanoparticle. The average mass transfer enhancement for 0.1 wt% CNTs could reach up to 2.48 times. In their study, surfactant named Arabic gum were used to get stable nanofluid by the means of ultrasonic vibrator. However, they did not investigate the effect of Arabic gum on mass transfer characteristics alone. Three kinds of nanoparticles, namely Al_2O_3, Fe_2O_3 and $ZnFe_2O_4$, were added into ammonia/water solution to study the ammonia absorption performance by Yang et al. [23]. They added sodium dodecyl benzene sulfonate (SDBS) into ammonia/water solution as surfactant. After that, mechanical agitation and ultrasonic vibration were exerted on the solution to obtain even and steady nanofluid. Different from the work done by Kang et al. [22], they investigated the influence of SDBS on absorption rate at first and pointed out that the absorption rate decreased with the increase of SDBS concentration. Then, the influence of nanoparticles on absorption was studied. Results showed that the absorption rate could only increase when the nanoparticles were evenly and stably dispersed in base fluid. The increment of effective absorption rate by adding Fe_2O_3 and $ZnFe_2O_4$ could be 0.7 and 0.5 respectively under certain operating conditions. Pineda et al. [24] investigated the CO_2 absorption characteristics by methanol with the adding of Al_2O_3 and SiO_2 nanoparticles. They used the sonication to disperse nanoparticles into methanol. Their experimental data indicated that the absorption rates were enhanced by up to 9.4% and 9.7% at the concentration of 0.05 % vol for Al_2O_3 and SiO_2 individually. In the work done by Kim et al. [25], they stated that the distribution stabilizer was required for the stable dispersion of nanofluid when the concentration of SiO_2 nanoparticle was greater than 0.01 %vol. They also carried out experiments to study the vapor absorption rate of $LiBr/H_2O$ soluiton with 0.005 %vol SiO_2 nanoparticles and 18% absorption enhancement was detected from their experiment results. In addition to experimental study, numerical investigation was also adopted by previous researchers [26,27]. Ali et al. [26,27] numerically studied the heat and mass transfer performance of liquid desiccant by adding Cu-ultrafine particles.

From the foregoing literature review, it is found that even though there are some studies related to the mass transfer with nanofluid applied in bubble absorption [15–21] and absorption refrigeration [22,23,25], no works on liquid desiccant dehumidification were reported. What is more, according to the research by Yang [23] and Kim [25], the adding of surfactants for nanofluid stability plays an important role in the mass transfer process. However, some researchers failed to investigate the effect of surfactant on the mass transfer alone, such as Lee et al. [19] and Kang et al. [22]. The present study focused on the dehumidification performance of $LiCl/H_2O$ solution with the addition of multi-walled carbon nanotubes (MWNTs). The even and steady $LiCl/H_2O$-MWNTs nanofluid was firstly prepared by adding PVP surfactant with mechanical methods. Then the dehumidification performances of adding PVP to solution and adding nanofluid to solution were identified separately. In order to uncover the mass transfer enhancement mechanism, parameters, such as wettability, contact angle of solution, film thickness and thermal conductivity, were measured and compared.

2. $LiCl/H_2O$-MWNTs nanofluid preparation

The MWNTs used in present study were purchased from Suzhou Hengqiu Graphene Co. LTD. They have the inner diameter of 3–5 nm and outer diameter of 8–15 nm. Their lengths range from 3 to 12 μm. The SEM image of MWNTs is shown in Fig. 1. The MWNTs usually intertwine with each other. Therefore, under normal conditions, it is hard to disperse nanoparticles in base fluid evenly and stably, which was also addressed by Kim et al. [25]. In practice, various methods, such as mechanical agitation, grinding, ultrasonic vibration and chemical stabilizer, are adopted to obtain stable nanofluid [28]. After various attempts, the present study chose polyvinyl pyrrolidone (PVP) as the surfactant to get stable nanofluid. In order to select appropriate concentration of PVP, concentration from 0.1 to 0.4 wt% were tested. The PVP was firstly dissolved in LiCl solution by mechanical agitation. Subsequently, the MWNTs were added into the solution with 1 h stirring at 1300 rpm. After that, 2 h' ultrasonic vibration was exerted on the